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HYDROGEN SORPTION CRYOCOOLERS FOR THE PLANCK MISSION

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ABSTRACT

Two continuous operation 18 K/20 K sorption coolers are being developed by the Jet Propulsion Laboratory (JPL) as a NASA contribution to the European Space Agency (ESA) Planck mission that is currently planned for a 2007 launch. The individual sorption coolers will each be capable of providing a total of 230 mW of cooling at 18 K and 1.45 W at 20 K given passive radiative precooling at 50 K. The hydrogen sorption coolers will directly cool the Low Frequency Instrument HEMT amplifiers to approximately 20 K and will also serve to intercept parasitics and precool a RAL 4.5 K closed-cycle helium J-T cooler to 18 K for the separate High Frequency Instrument. The operating conditions and mission requirements for the Planck sorption cooler are presented. The concept design of the 20 K coolers is described along with the predicted performance. $La_{1.01}Ni_{4.78}Sn_{0.22}$ hydride sorbent beds are currently in fabrication and initial test data on their performance are presented.

INTRODUCTION TO PLANCK

Planck, the third Medium-sized ESA mission M3, will be launched in 2007 in combination with the Far InfraRed and Sub-millimetre Telescope (FIRST). Planck will carry two instruments: the High Frequency Instrument (HFI) and the Low Frequency Instrument (LFI). Together they will observe and image the full sky in nine spectral bands between 30 and 857 GHz. The LFI utilizes an InP HEMT amplifier radiometer cooled to 20 K through a combination of passive cooling to <50 K and the hydrogen sorption coolers. The HFI observes using bolometers cooled to 100 mK through a combination of passive coolers, the 18 K/20 K sorption cooler, a 4.5 K RAL Mechanical J-T cooler and an Benoit style open cycle dilution cooler[1].

Planck is the third generation space mission (following COBE and MAP) to be designed for observation of the Cosmic Microwave Background (CMB) anisotropies. Planck will observe the full sky and produce maps with an accuracy limited only by cosmic variance and astrophysical foregrounds at all angular scales larger than 10' for the LFI and 6' for the HFI. In addition, both instruments will be capable of measuring the polarization in the CMB. The unprecedented angular resolution and sensitivity ($\Delta T/T \sim 2 \times 10^{-6}$) will allow the primary cosmological parameters (Hubble constant, deceleration parameter, curvature of space, baryon density, amplitude and spectral index of the primordial scalar density perturbations, and the gravity wave content of the Universe) to be determined to an accuracy of a few percent. In doing so a number of truly fundamental questions will be answered about our Universe: How fast is the Universe expanding? What is the ultimate fate of the Universe? What are its material constituents (baryons, dark matter,…)? Where did the initial perturbations come from? When did the first structures form in the Universe? What is the nature of particle physics at energies $\simeq 10^{16}$ GeV?

PLANCK PAYLOAD DESIGN OVERVIEW

As with most fundamental physics experiments, the data to be taken by Planck are more coupled to the specifics of the experimental apparatus and environment than to the science of interest. Uncertainties or oscillations in pointing, supply voltages, thermal fluctuations, straylight (much of this is thermal emission from different surfaces) all impact the data collected by the instrument. As an example, the spacecraft emits approximately 10^3 W. The HFI is sensitive to energy levels on the order of 10^{-18}W. As a consequence, even extraordinarily minute spacecraft thermal emission fluctuations that reach the HFI detector could be confused with sky emission.

Changes over some timescales, especially at about the 1 minute spin period, are particularly critical, as they are difficult to distinguish from the observed sky. Even worse, this does not mean that these changes necessarily have a frequency of 0.01667 Hz; but only that they have a non-zero Fourier component at this frequency. The result is that the mission configuration and design, along with the instrument designs, operational and data analysis strategies, must all be driven to minimize systematic effects on the final science data products by reducing the level of these effects and ensuring that they are well understood so that the residual effects can be confidently removed in software without adversely affecting the science results. Ensuring the successful accomplishment of the science goals is the major factor affecting the mission design, and therefore the 18/20 K coolers design.

Planck will fly in a Lissajous orbit around the Earth-Sun L_2 point, and spins at about 1 rpm about an axis that points towards the sun. The 1.5 m aperture telescope looks 80° to the spin axis and scans circles in the sky. Figure 1 shows a crossection view of a likely configuration for the Planck spacecraft. As the Architect Study is still underway, some changes from this figure will occur.

All warm components of the instruments are mounted on the service module. This includes not only the instrument electronics but the warm compressors of the sorption coolers and the RAL 4.5 K mechanical J-T cooler, the gas storage tanks for the dilution refrigerator and all their associated electronics. The optical bench and telescope are thermally isolated from the warm spacecraft bus by low conductance struts and v-groove shields. V-groove shields are a set of two or more angled low-emissivity specular surfaces typically 2 to 5 degrees out of parallel. The radiative heat transfer between two facing surfaces of the V-groove shield with emissivity ε is proportional to ε^2, while that between infinite parallel planes is $\varepsilon/2$. The extra energy in the V-groove case is radiated to space. The V-groove shield therefore can provide extremely good radiative isolation between objects at different temperatures even with surfaces of only moderately low emissivity. In addition, it can be highly efficient at intercepting conductive thermal loads and radiating them to space. The reduction in heat transfer in this arrangement is significantly superior to that typically achieved by conventional Multi-Layer Insulation (MLI) between two parallel plates. The v-groove design concept was originally invented by Ray Garcia at

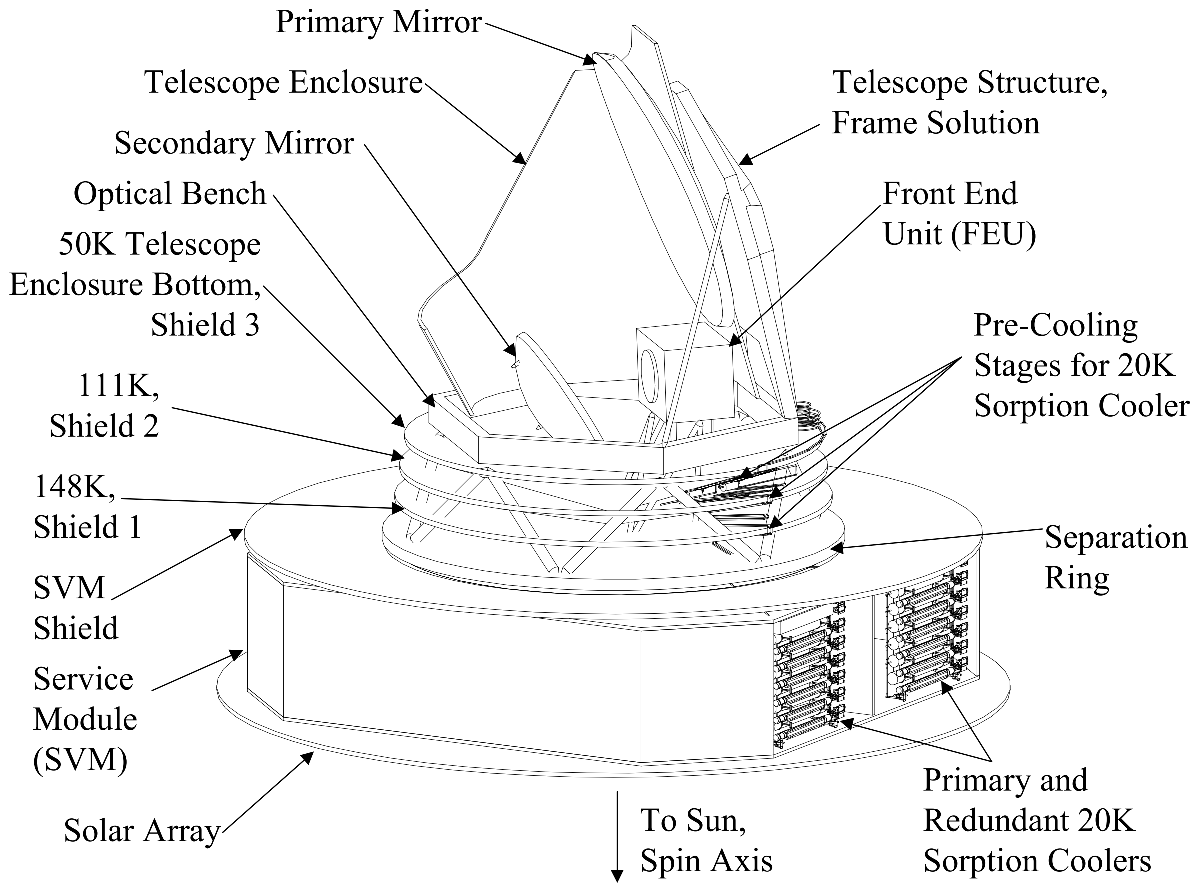

Figure 1. The Planck configuration optimizes passive radiative cooling and minimizes straylight and other systematic effects on the final science data.

JPL. Since then this new technology has been validated in thermal vacuum and vibration tests[2,3]. Similar 'bounce-view-of-space' tricks are commonly employed in high performance radiators (e.g. the NIMS radiative cooler for the Galileo orbiter[4]) and therefore substantial flight heritage date exists for evaluating the long term behavior of such surfaces.

The current estimates for shield temperatures are 148 K for the first thermal shield, 111 K for the second and 50 K for the telescope enclosure[5]. The Front End Unit (FEU) is located within the telescope enclosure. This contains the frontend radiometer of the LFI as well as the HFI bolometer array.

PLANCK 18 K/20 K COOLERS OVERVIEW

Two sorption coolers will be flying on the Planck mission. One will provide the primary cooling of up to 230 mW at 18 K for HFI parasitic interception and RAL 4.5 K J-T cooler precooling, and up to 1.45 W of cooling at 20 K for the LFI. The second will be turned off and used as a backup unit should anything happen to the primary cooler. Each cooler is sized to achieve a two year operating life. The cooler input power is 520 W at end-of-life plus an additional 30 W estimated for the cooler electronics. Figure 2 shows a schematic of the sorption cooler that will be used on the Planck spacecraft.

The inherently split design of continuous operation sorption coolers both enables, and maximally benefits from, the passively cooled design needed to minimize systematic impacts on the data gathered but which requires the spacecraft to be located over a meter from the 20 K Front End Unit. The very long operating cycle of the sorption cooler enables easy thermal fluctuation characterization and removal from the science data.

The compressor assembly shown in figure 3 is composed of six identical sorption compressor elements, each filled with metal hydride and provided with independent

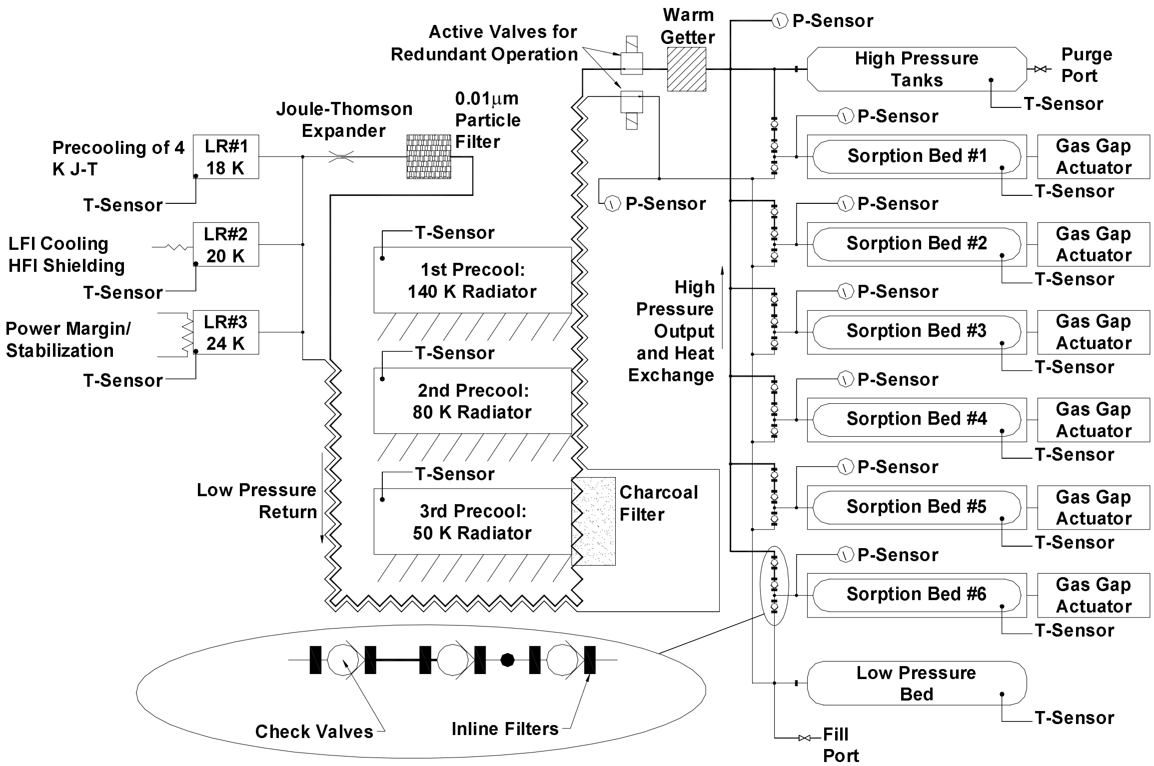

Figure 2. Planck sorption cooler schematic.

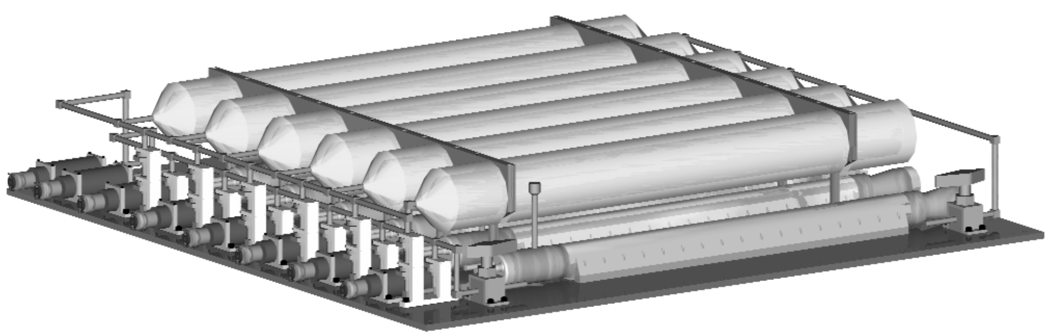

Figure 3. Planck sorption cooler compressor assembly

heating and cooling which will be described later. Each compressor element is connected to both the high pressure and low pressure sides of the plumbing system through check valves, which allow gas flow in a single direction only. The check valves are indicated on the schematic as single arrows, which indicate the direction of gas flow through them. In addition to the compressors, there are five one-liter high-pressure stabilization tanks connected to the high pressure side of the system to damp out oscillations of the high pressure gas, and a low pressure stabilization sorbent bed to damp out pressure fluctuations of the low pressure gas.

Refrigerant travels from the compressors through a series of heat exchangers and radiators, which provide precooling to approximately 50 K, through the J-T expander at the FEU. The cold end assembly shown in figure 4 includes three liquid reservoirs in the system: a first reservoir providing 18 K cooling of the 4.5 K RAL mechanical J-T and the HFI thermal shielding, a 20 K reservoir providing cooling to the LFI, and an overflow reservoir for unused cooling capacity. Each of the reservoirs is filled with a wicking material in order to retain the liquid in the reservoirs without gravity. The third reservoir is maintained above the hydrogen equilibrium temperature, to wick and then sublimate any liquid which reaches it, providing an even gas flow back to the sorbent bed.

All regulation of the system is done by simple heating and cooling, with no active control of valves being necessary. Normal operation of the compressors can be done with only a minimum of active feedback: The heaters for the compressors are controlled by a simple timed on-off heater system. In addition to the on-off heater power, each heater will have up to 30 W of additional heating supplied by a proportional controller to compensate for any degradation of hydride or gas-gap properties that might occur.

Compressor Assembly

The compressor assembly is comprised of the six compressor elements, high-pressure stabilization tanks, the low pressure stabilization bed, check valves, and manifolding. The switch time is 667 s leading to an overall cycle time of 4000s. The compressor assembly mounts directly onto the heat rejection radiator. This radiator is sized to reject the cooler input power at 270 K +10 K/-20 K. The low heat rejection temperature was selected to ensure precooling of the 4.5 K RAL cooler at less than 19 K. The compressor assembly mass is 40 kg. It's volume is 0.25 m x 0.8 m x 0.8 m.

A single compressor element is comprised of two concentric cylinders closed with end caps. The inner of these tubes contains the $La_{1.01}Ni_{4.78}Sn_{0.22}$ hydride material and the outer forms a vacuum jacket around the inner cylinder. An exploded view of an compressor element is shown in figure 5. This vacuum jacket is used as a gas-gap heat switch. A recently assembled compressor element which is being used for gas-gap thermal switch characterization is shown in figure 6. The hydrogen gas for the gas-gap heat switch is supplied through a tube penetrating the side of the outer cylinder.

The heater passes through the hydride material and is designed to uniformly distribute heat to ensure a high degree of temperature uniformity when at the maximum temperature of 465 K. Heat transfer to the hydride is provided by aluminum foam that fills the inner cylinder and makes tight contact to the heater. The foam is 89% empty, and is cut to allow penetration by the various other components, which are located in the inner cylinder. A vent tube passes through the center of the hydride material. This vent tube is fabricated from sintered 316 stainless steel, and has a sub-micron porosity, which excludes the powdered hydride from the hydrogen gas flow.

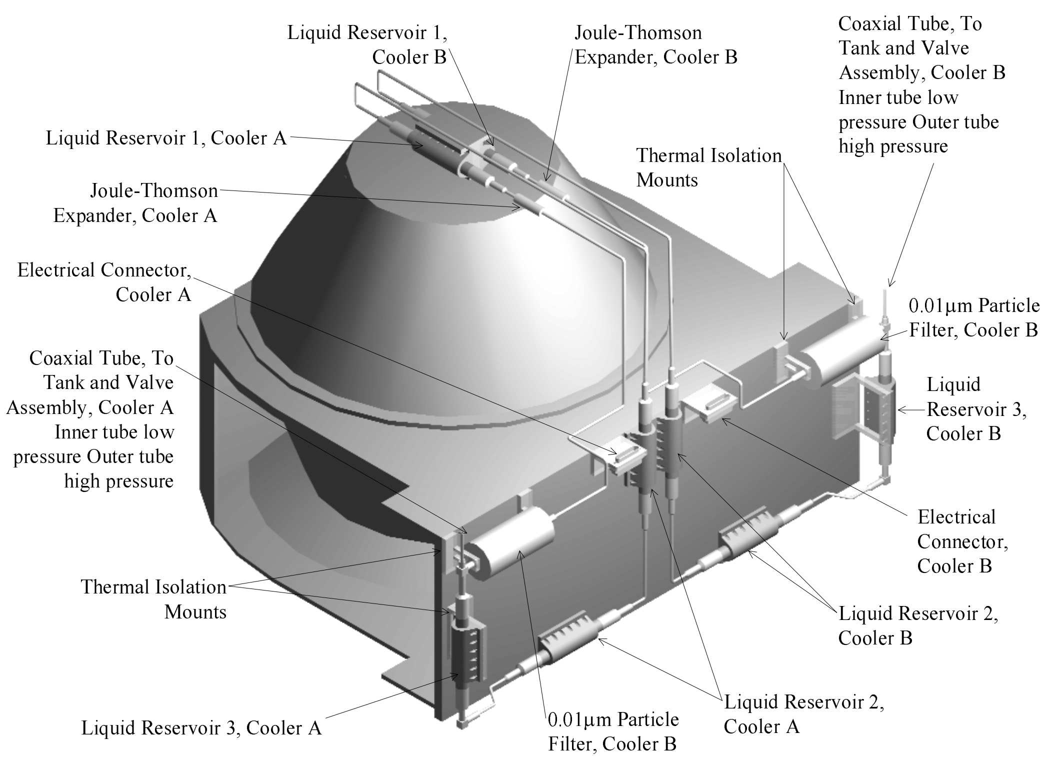

Figure 4. Planck sorption cooler cold end assembly

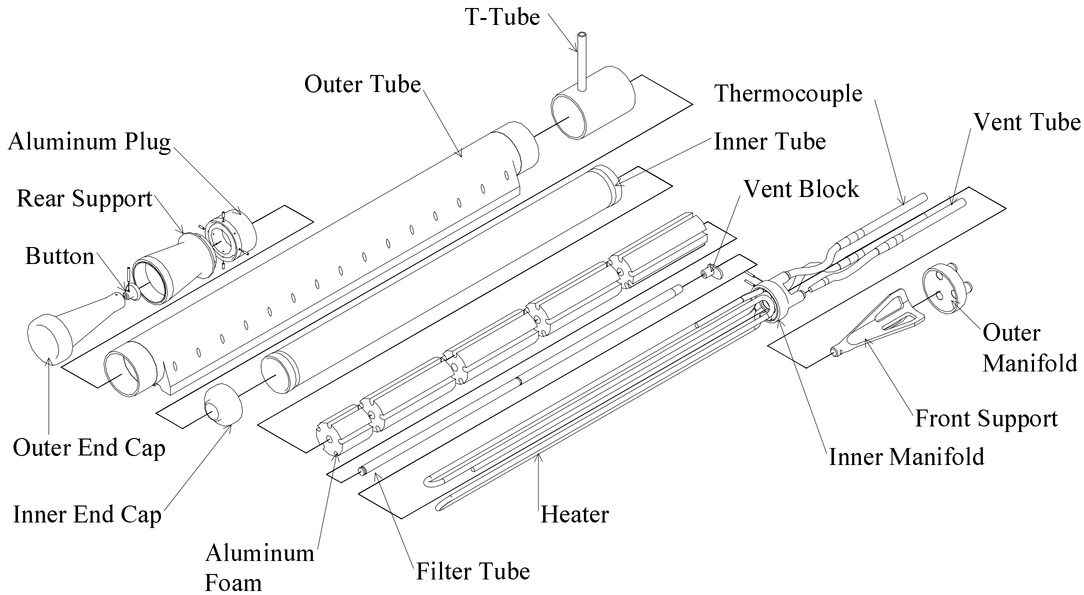

Figure 5. Exploded view of compressor element piece parts.

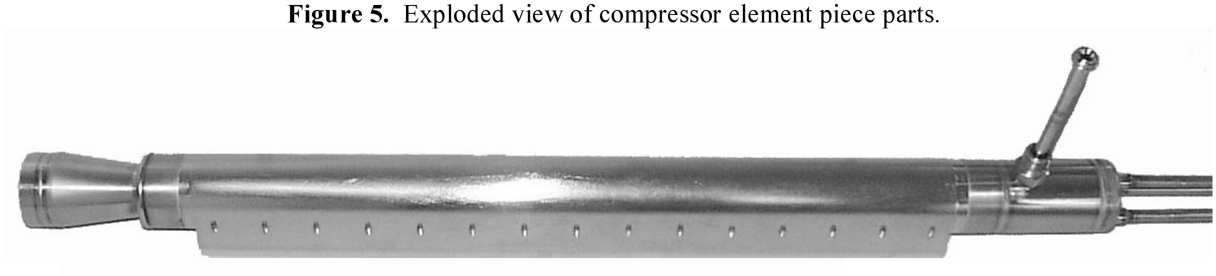

Figure 6. Compressor element used for gas-gap characterization tests.

A heater, thermocouple, and vent-tube lead run from the end cap of the inner cylinder to that of the outer cylinder. Each has a small bend for stress reduction, which defeats the potential for any of these elements to carry load. Therefore the only elements taking significant load are those designed to be structural, load carrying elements. There are two of these structural end supports: one at either end of the tube assembly. At one end provision is made for thermal compliance, without strain, between the inner and outer tubes. The outer tube assembly is primarily fabricated of 6061-T6 aluminum. This outer tube also provides the primary structural attachment point for the single compressor bed.

Nearly all parts of the compressors and the gas-handling system which come in contact with hydrogen are made of 316L vacuum arc remelt (VAR) stainless steel which has been electropolished on the surfaces exposed to the hydrogen. This choice of material also serves to prevent the degradation of the compressors structural parts by reaction with the hydrogen. There are two components which are made of other materials. The aluminum foam, which provides heat conduction to the hydride in the compressor, and the seals of the check valves, which are made of Viton. Stringent cleaning and assembly methods are used during construction.

The space between the inner compressor vessel and the outer tube assembly is used as a gas-gap thermal switch. It is preferred that this switch be operated in a closed cycle using a hydride to pump the gap to approximately 0.01 Torr when 'off' and to approximately 10 Torr when 'on.' A test program is currently in place to characterize candidate materials and to determine the operational pressure requirements for closed cycle operation[6]. Closed cycle operation will require approximately 8 W per switch which is 'on.'

In figure 7 conductance test data at approximately 300 K is presented for the compressor assembly shown in figure 6. The sum of conductive and radiative parasitics at the highest temperature difference (475 K inner vessel and 289 K outer vessel), which occurs in operation with the gas-gap volume evacuated, is 31 mW/K. This is slightly better than the predicted performance of this assembly. The conductance across the gas-

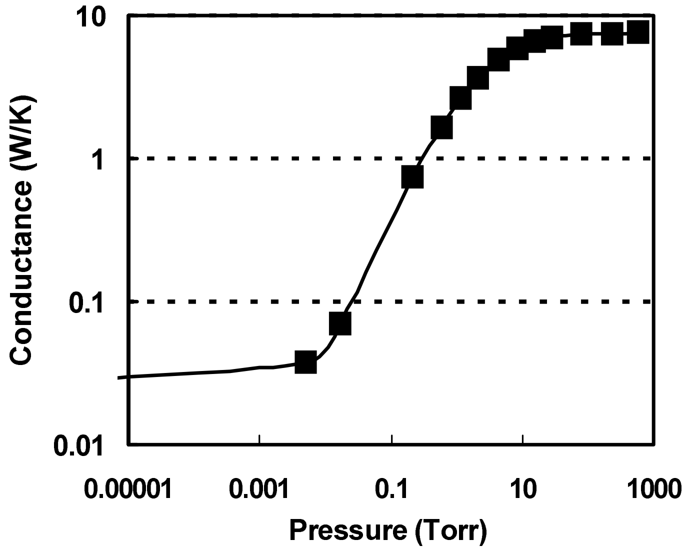

Figure 7. Gas-gap conductance from rarified gas regime through continuum flow at approximately 300 K.

gap matches theoretical predictions based on a model with one adjustable parameter, the accommodation coefficient, which has a value of 0.4. At high pressure (above approximately 30 Torr) the gas-gap switch conductance saturates at approximately 7.8 W/K, in good agreement with expectations.

J-T Cryostat Assembly

The J-T cryostat assembly includes a warm contaminate filter, active valves to allow redundant operation of the coolers, four heat exchangers, an approximately 50 K charcoal filter, an approximately 30 K 0.01 micron particulate filter, a porous plug J-T expander, and three liquid reservoirs. The four tube-in-tube heat exchangers are all 6.35 mm outer diameter tubing with a 3.18 mm outer diameter inner tube. The high pressure gas is held in the annulus. The heat exchangers are heat sunk at each thermal shield.

Contaminate trapping is done at room temperature with either a hydride getter or a resin bed (to be determined), with activated charcoal and a particulate filter at 50 K and a 0.01 micron filter at ~30 K. All of the components at the cold end were shown in figure 4. The J-T expansion is done through a porous plug device nearly identical to those described previously[7]. The first two liquid reservoirs are designed to separate the liquid refrigerant from the two-phase fluid leaving the J-T expander. This fluid is wicked to the wall of the reservoirs. The fluid in each reservoir is at essentially the same pressure and temperature. However the heat flux into each is very different. The first liquid reservoir interface temperature is approximately 18 K when providing < 230 mW of refrigeration to the HFI and the 4.5 K RAL cooler. The second reservoir has an approximately 20 K interface temperature due to the higher heat flux from the LFI. The third reservoir is designed to vaporize any excess liquid refrigerant to ensure a stable mass flow and pressure at the cryostat. This helps significantly to remove temperature fluctuations in the range of 1 Hz.

Figure 8 presents the predicted performance of the Planck sorption coolers as a function of temperature as compared with the predicted combined instruments cooling requirement. The difference between these predictions is the predicted margin. At a precooling and telescope enclosure temperature of 50 K, a 77 % margin is predicted. With an environment of 60 K the margin is 0%.

The flight cooler electronics and software will be supplied by the Institut d'Astrophysique Spatiale in Orsay France and an industrial partner. The electronics consist of a CPU, relay boards and several temperature and pressure sensor boards. The details of these electronics will be presented in a future paper.

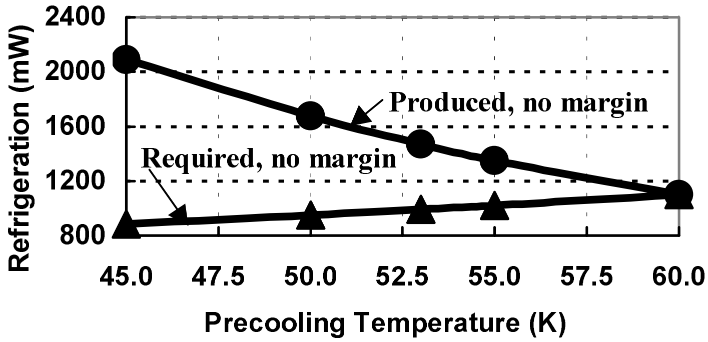

Figure 8. Predicted performance of the Planck sorption coolers and predicted combined Planck instruments cooling requirement as a function of precooling/telescope enclosure temperature.

DEVELOPMENT PLAN SUMMARY

1999 and 2000 will be primarily spent completing the technology development for this program. In 1999 an accelerated lifetest of the hydride material will be performed, several compressor elements will be built and begin parametric performance tests, gas-gap and characterization and actuation materials testing will be completed, and a demonstration of a three liquid reservoir cryostat will be made. In 2000, this development will continue leading up to initiation of testing of a flight-like ‘elegant breadboard cooler’ in December. The qualification model cooler is scheduled for delivery in January 2003. After qualification, this cooler will be refurbished and fly as the redundant cooler. The flight model cooler will be delivered in January 2004.

SUMMARY

A pair of sorption coolers are being developed for the ESA Planck mission. These coolers will be combined with passive cooling, a 4.5 K RAL cooler and a Benoit style dilution cooler to provide refrigeration. The resulting cryogen-free mission design will likely prove a pathfinder for many other future astrophysics missions.

ACKNOWLEDGMENT

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